

Research paper

An investigation of farm-scale adaptation options for cotton production in the face of future climate change and water allocation policies in southern Queensland, Australia



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ABSTRACT

Modelling cotton production at the farm-scale provides insight into the importance of water management options in adapting to climate change, especially given the renewed focus of government policies on irrigation water access and allocations. Using an irrigated cotton farm in southern Queensland as a case study, we investigated two possible adaptation strategies in response to changes in water resources from projected climate change (CSIRO Mk3.5, A1FI scenario). The modelled farm produced irrigated cotton, wheat, maize, and non-irrigated sorghum. The adaptation Strategy 1 allowed the substitution of current (baseline) production system with a system of less intensive cotton (2 m row spacing) and a maximum of 2 in-crop irrigations instead of 4. Whereas Strategy 2 allowed for the production option of dryland cotton in the rotation and implied as much 2 m row spacing cotton planting as possible depending on the other cropping rules regardless of the state of water storages. These two strategies were examined using a bio-economic farm enterprise model by evaluating the effects of projected changes in yield, water use and farm profitability (gross margin, GM), which resulted from crops competing for resources (i.e. irrigation water). Results showed 14% less water available in the 2030s and 2050s compared to the baseline (1960–2010), as a result of climate change and water policy decisions, thereby reducing the input costs. Under Strategy 1 there were 12.1% and 4.4% yield decreases in 2030 and 2050, respectively; while under Strategy 2 the inter-annual yield variability and proportion of low yields (<5 bales/ha) increased over the same periods. Without adaptation GMs were reduced by 27% and 43% in 2030 and 2050, respectively. Strategy 1 resulted in 8.8% increase and 15.8% decrease in 2030 and 2050, respectively. However with Strategy 2, GM increases were observed (49% and 12%, respectively in 2030 and 2050). Moreover, without appropriate adaptation options, the enterprise would have to reduce the area of irrigated cotton, causing reductions in farm business gross margins. Our findings suggested that decreased water availability would not significantly impact the cotton production system and profitability if suitable adaptation options are available.

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1. Introduction

Climatic variation is a fundamental determinant of cotton production in Australia (CRDC, 2011; McRae et al., 2007). The gross value of cotton produced in Australia has generally increased since 1985, except during drought years including 1986/87, 2002/03, 2003/04, 2006/07, 2007/08 and 2014/15 (Cotton Australia, 2015; McRae et al., 2007; NLWRA, 2008; van Dijk et al., 2013). Neg-

ative effects of climate change, i.e. reduced water availability and increased evaporation, are likely to exacerbate other climate-related production challenges to the Australian cotton industry through fruit loss, lower yields and reduced water use efficiencies due to higher temperatures (Bange et al., 2010; Williams et al., 2015).

The Australian cotton industry is one of Australia's largest rural export earners (Cotton Australia, 2016; Cotton Australia and CRDC, 2014). In cotton-producing regions in Australia cotton is a major component of the farming system and makes up 30–60% of the gross value of the total agricultural production (ABARES, 2012; Cotton Australia and CRDC, 2014; Roth, 2010). Most of cotton

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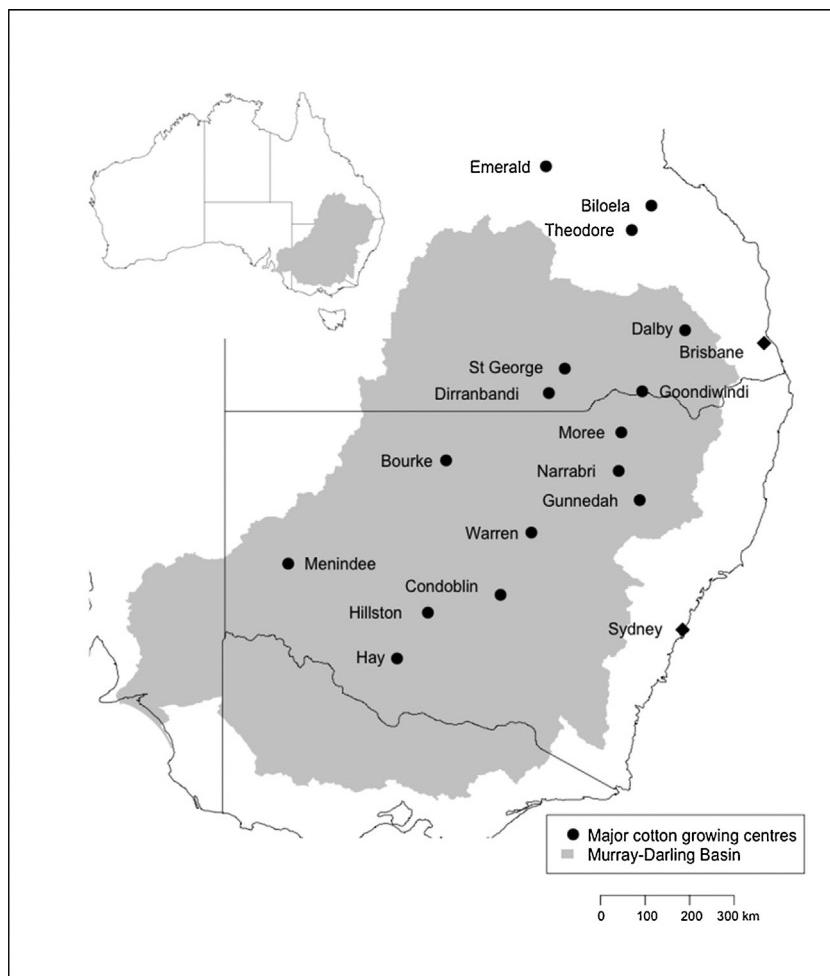


Fig. 1. Cotton growing centres in Australia in relation to the Murray-Darling Basin.

producing farms in Australia ($\geq 80\%$) are irrigated. The overall production is therefore sensitive to water availability. Water resources allocation regimes vary significantly depending on the particular state or territory, the environmental conditions and water management capacities. Water resources allocations in Australian cotton producing regions (Fig. 1) depend on the Murray-Darling Basin (MDB) plan 'The Plan'. The Plan aims to ensure that water is shared between all users, including the environment, in a sustainable way (<https://www.mdba.gov.au/basin-plan>). However, the Plan lacks robust understanding of what is sustainable and what is not, and how to best balance and optimise the water needs of the environment, agriculture, other non-agricultural industry, and human settlements (Kiem, 2013). Under the proposed water buy-back scheme, the northern MDB region's allocation is expected to reduce by 100 GL or 14%, and to increase flows in the Murray–Darling River system (Kiem, 2013; MDBA, 2010). Together with significant and unanticipated declines in water allocations over recent years and climate change threat this will result unprecedented pressure on cotton irrigators to improve water use efficiency, productivity and adopt suitable practices to remain viable.

The sensitivity of cotton production to various key aspects of climate (such as temperature, radiation, water, CO₂) has been well documented (e.g., Bange et al., 2010; Bange and Milroy, 2004; Reddy et al., 1995; Reddy et al., 2000; Reddy et al., 2004). This knowledge has enabled the development of strategies to manage the impacts of climate variability at both farm and industry scales. In general, these strategies have focused on improving the whole farm resource and crop water use efficiencies to increase farm pro-

ductivity and economic returns (Power et al., 2011; Ritchie et al., 2004). Despite this, there are still significant uncertainties surrounding the impacts of climate change on cotton production and possible adaptation options, especially in light of changing government policies on irrigation water access and allocation (Luo et al., 2013; McRae et al., 2007; MDBA, 2011; Pearson et al., 2011).

To address these uncertainties, the vulnerability and sensitivity of cotton yield to climate change has been assessed for the major cotton producing regions using a range of modelling techniques including process-based models (Doherty et al., 2003; Haim et al., 2008; Hebbal et al., 2013; Rodriguez et al., 2014; Williams et al., 2015; Yang et al., 2014) and statistical modelling (Schlenker and Roberts, 2009). Such quantifications of the risk of climate change to the cotton industry can provide the foundations for an economic analysis of climate change impacts, as undertaken for other agricultural sectors (e.g. Rodriguez et al., 2014).

Existing analyses on impacts of climate change on the yield of individual crops present considerable potential for adaptation and policy recommendation (Challinor et al., 2009; Howden et al., 2010). Suggested climate risk management strategies for Southern Queensland include water management strategies to enable better water use efficiently, improved nitrogen use efficiency, development of crop rotation systems, optimal planting configurations, the use of integrated pest and weed management systems (Bange et al., 2010; Luo et al., 2013; McRae et al., 2007). However, it is essential that the spatial scale be increased to the farm level when considering adaptation plans for cropping systems (Rodriguez et al., 2011). Working at a farm-scale will demonstrate to farm managers

how to make decisions related to farm business profits, risks, and cost-benefit analyses between alternative management options (Rodriguez et al., 2014). Williams et al. (2015) used the Agricultural Production Systems Simulator model (APSIM; Holzworth et al., 2014; Keating et al., 2003) with future climate change scenarios to provide information at the crop-level on the impact of climate change on cotton yield for Southern Queensland. A prerequisite of the simulated cotton growth in those experiments was the maintenance of available soil water (ASW) at 65%. This required irrigation volumes to be increased by 47.4% in the 2030s and 48.7% in the 2050s. Although it highlighted the magnitude of the problem in the future, the analysis did not guide decision-making since managers would have to make decisions on the level of irrigated versus non-irrigated and the overall crop mix and planting system. Exploring such aspects in a more realistic manner requires at least farm-scale simulations.

The aim of this paper was therefore to investigate the potential of a farm-scale model of cotton production on the Darling Downs region of southern Queensland in order to increase our understanding of the effect of climate change and water policy on yields and gross margins, and to develop plausible adaptation strategies. Previous approaches (Power and Cacho, 2014; Power et al., 2011) have used bio-economic models to simulate grain-cotton enterprises on the Darling Downs. The novelty of our approach was to compare the adaptation strategies suggested after consultation with the collaborating farmer, rather than focussing on identifying optimal farm management strategies.

2. Materials and methods

We developed different scenarios incorporating national water policy and farm business practices on a typical cotton production system in the Darling Downs region of southern Queensland (Fig. 1). Projected changes in rainfall, temperature and CO₂ are reflected in modelled crop growth and yield. Under future climate scenarios, adaptation strategies will be required to manage reduced in-crop rainfall and irrigation water availability. Plausible strategies were identified in consultation with cotton producers and are discussed in detail in the following sections.

2.1. The farm level assessment model

APSIM's multi-field capability was used to develop a farm level model. Farm management, such as crop sowing rules that determine what crop to sow in which field or the movement of water to irrigate crops, was implemented by a computer scripting language (de Voil et al., 2009) within APSIM. By using sowing rules the farm model will respond to the different climatic conditions of either historical or projected climates. If the sowing rules determine that no crop be planted then the field is in fallow. In such case a weed model (de Voil et al., 2009) which responds to climate conditions and cropping intensity is used to estimate fallow costs due to weed management.

Fertiliser rates at sowing were determined by the crop nitrogen requirements and were obtained by the collaborating farmer. A daily net balance of the soil nitrogen was modelled by APSIM's nitrogen module SOILN (Probert et al., 1998). This resulted in fertiliser amounts, and corresponding costs, which varied with seasonal conditions, cropping histories and intensity.

The timing and amount of irrigation applied to a crop was determined by the difference between crop demand and soil water supply. When extractable soil water falls below a critical value water is pumped from a water source, such as a storage or bore, to the field and the crop is irrigated. In some cases, when the level of the storage is sufficiently high, water can gravitate out and pumps

are not operated. The level of the storage below which water had to be pumped was obtained from the farmer during the interviews.

The on-farm water sources were modelled via instances of APSIM's WaterSupply module (Gaydon and Lissom, 2005) and were configured to be bores with annual allocation (ML), and two open storages which were subject to daily water losses due to seepage and evaporation and were "topped-up" from intercepted rainfall, off-farm overland flow and on-farm field runoff. The calculation of captured on-farm runoff into farm storages is given by:

$$R_{ML} = \min\{WS_{ML}, TL \sum_{i=1}^n \frac{r_i A_i}{100}\} \quad (1)$$

Where: R_{ML} is the total farm runoff (ML) calculated daily; WS_{ML} is the available capacity, in ML, of the farm water storage of interest; TL is the transmission loss from moving water from the fields into storages and is due to evaporation and drainage in channels; r_i is the runoff (mm) from field i and modelled by APSIM's soil water module SoilWat (Probert et al., 1998); and A_i is the area (ha) of field i .

The model's economic output, annual total farm gross margin (GM_{farm}), was calculated by assigning an economic value to every modelled event, such as crop sowing and harvests, weed events and operation of farm pumps. Crop prices and variable costs were obtained during interviews with the collaborating farmer and represented what the farmer would expect over the long term and hence excluded any recent movements. The annual total farm gross margin is calculated as follow:

$$GM_{farm} = \sum_{i=1}^{12} GM_{fieldi} \quad (2)$$

Where GM_{farm} is the aggregate gross margin for each field GM_{fieldi} for that year; GM_{fieldi} in a given year is the sum of revenue for all crops in a field i less costs. It is given by:

$$GM_{fieldi} = \sum (YPA - H_A A - H_Y Y - SA - N - F - I) \quad (3)$$

Where Y is the crop yield for cotton (ba/ha) or other crops (t/ha); P is the crop price (\$/(ba or t)); A is the crop area grown (ha); H_A is the aggregate area-dependent harvest costs (\$/ha) and H_Y is the aggregate yield dependent harvest costs (\$/(ba or t)); S is the aggregate sowing costs (\$/ha); N is the costs of fertilisers applied to the field (\$); F is the fallow cost which is the cost to spray every weed event generated from the weed model (\$); and I is the irrigation cost (\$) for a crop in that field; it is calculated as follow:

$$I = \sum (WS + B + T + WH) \quad (4)$$

The irrigation costs (Eq. (4)) are the sum of all pumping costs (\$) from water storages (WS) and bores (B), pumping of return tail water (T) and water harvesting costs (WH). WH is a variable cost and is calculated for each cropping enterprise in a year by apportioning the pumping costs to harvest the overland flow based on the amount of applied irrigation to each crop for the year.

2.2. The case study farm

As described by Power and Cacho (2014) the case study farm was 446.5 ha irrigated grain-cotton enterprise situated on the eastern Darling Downs, Queensland (Fig. 1). It comprised 12 fields which a previous soil classification (Dalglish and Foale, 2005) has described as a black vertosol Mywybilla (APSoil database No. 900). The details of the farm fields are listed in Table 1. Each field was irrigated from captured on-farm runoff collected into one of two on-farm water storages. The timing and choice of either cotton, maize, wheat or sorghum crop to sow in each field was determined

Table 1

Farm fields, areas and water storage for irrigation. The soil type is a black vertosol Mywybilla (APSoil database No. 900).

Paddock	Area (ha)	Water storage
1	42	West
2	33	West
3	37.5	West
4	21.5	West
5	40	West
6	56	West
7	40	East
8	40	East
9	42	East
10	26	East
11	48	East
12	20.5	East
Total Area	446.5	

Table 2

Crop sowing rules.

Crop	Sowing rules
Maize	Date between Sep 15 and Sep 30 Farm area planted to maize <40 ha Previous crop not maize Days past since a harvest >14 Available stored water >3ML/ha
Cotton	Date between Oct 1 and Oct 31 Previous crop not cotton Farm area planted to cotton <162 ha Days since a harvest >14 Available stored water >4ML/ha
Sorghum	Date between Nov 1 and Nov 15 Rain over 3 days >30 mm Soil water profile >50% Days since a harvest >14
Wheat	Date between Jun 1 and Jun 30 Farm area planted to wheat <80 ha Rain over 3 days >30 mm Days since a harvest >14
Wheat	Date equals Jun 30 Farm area planted to wheat <50 ha Days since a harvest >14

by evaluating the rules listed in **Table 2**, with cotton given a priority. The stored water, listed in the sowing rules, could be either bound to a parcel of land as soil water, or unbound water for irrigation that was stored in either on-farm open water storages or as un-used bore allocation. These rules were used to allocate farm area to be planted to each crop as a function of stored water at the time of sowing and were not an indication of the required water to grow a successful crop. **Table 3** lists the agronomic parameters for each crop. Sorghum was not irrigated and therefore there was no irrigation threshold. For more details about the implementation of farm management see [Power and Cacho \(2014\)](#).

The case study farm employed furrow irrigation was implemented in the model pumping 25% more water than was required to fill the soil profile from the storage. Transmission losses due to drainage and evaporation were incurred at a rate of 10% of the amount pumped from the storage to the field and for the return of tail water. These percentages and additional pump capacities

Table 4

Parameters for farm water storages and bore.

Water storages/sources	West storage	East storage	Bore
Capacity (ML)	350	450	200 ^b
Surface area (ha) ^a	6.6	7.8	NA ^c
Supply rate (ML/day)	5.0	8.0	1.5
Harvest rate (ML/day)	96	96	NA
Paddocks	1 to 6	7 to 12	NA
Total cropping area (ha)	230.0	216.5	NA

^a Storage surface area at capacity.

^b Annual allocation.

^c Not applicable.

were supplied by the collaborating farmer. Corresponding pump operating times were calculated. Pumping costs due to operation and maintenance of pumps also incurred.

Irrigation water was supplied by two on-farm storages, labelled East and West (**Table 1**), with a combined capacity of 800 ML and each supply irrigation water to fixed farm fields with combined areas of 230 and 216.5 ha for the West and East storages, respectively. The farm had a number of bores with an annual allocation of 200 ML per year with 100% carryover (i.e. 100% of any unused allocation can be carried over to the following year). **Table 4** lists the model parameterisation of each source of irrigation water.

Detailed prices and variable costs for each cropping enterprise and farm pumping costs were elicited from the farmer and are available in the Supplementary Tables S1–S5. These economic values were maintained at present values so that the effect of climate change on farm profitability could be more easily identified.

2.3. Climate projections

The crop and farm simulation models require daily meteorological data. We used the Dalby Post Office meteorological recording site (Bureau of Meteorology site number: 041023, latitude: 27.18°S, longitude: 151.26°E) to represent the Dalby District of the Darling Downs in southern Queensland. Historical weather data (maximum and minimum temperatures, solar radiation, and rainfall) for 1960–2010 were sourced from the SILO historical dataset (<http://www.longpaddock.qld.gov.au/silo>; [Jeffrey et al., 2001](#)).

Future climate change scenarios were based on the CSIRO Mk3.5 general circulation model simulation using the A1FI SRES emissions scenario ([IPCC, 2000](#)). This is the highest emission scenario. It is described as the “business as usual” emissions pathway, that is, future emissions occur at historical rates with no mitigation strategies implemented. It is most similar to the Representative Concentration Pathway 8.5 as used in the Fifth Assessment Report. As shown by [Fuss et al. \(2014\)](#) this emission scenario matches the observed emissions. Maximum and minimum temperature, solar radiation, rainfall data for 2030 and 2050 were obtained from the SILO Consistent Climate Change Scenarios (CCS) database (<https://www.longpaddock.qld.gov.au/climateprojections>; [DSITI, 2015](#)). CCS projections data for 2030 (or 2050) were 30-year period data centred on that year. A summary of the CSIRO Mk3.5 rainfall scenarios is presented in [Fig. 2](#).

Table 3

Crop agronomy parameters. Soil N levels at sowing indicate the total amount of soil nitrogen required at sowing; irrigation thresholds are expressed as a fraction of the full soil profile.

Crop	Variety	Plant density (plants/m ²)	Soil N at sowing	Fraction of full profile	Max in-crop irrigations
Cotton	S71BR	10	240	0.65	4
Maize	dekalb_xl82	8	220	0.40	2
Sorghum	early	4.5	50	NA ^a	NA
Wheat	hartog	120	200	0.40	2

^a Not applicable.

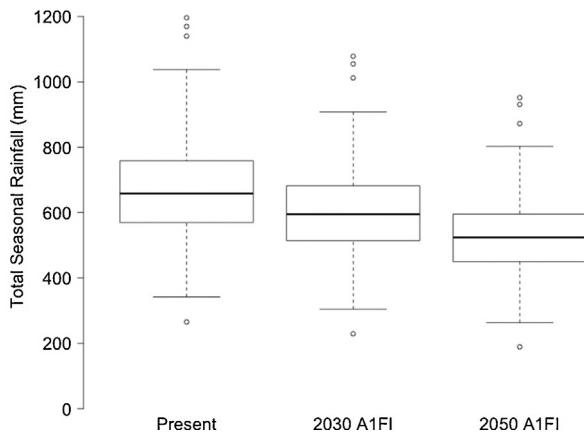


Fig. 2. Rainfall received at Dalby during the crop year for the present climate and the future climates in 2030 and 2050 as simulated by CSIRO3.5 using the A1FI emissions scenario.

The bore allocation was reduced by 14% to 172 ML/year for years 2030 and 2050 to simulate possible reductions that might occur. The MDB plan (MDBA, 2011) offers a wide range of estimates for possible reductions in water allocation for the Condamine catchment. We therefore selected a scenario which was neither negligible nor extreme. Applying the same allocation for 2050 as for 2030 is a conservative position but the policy horizon is too far to make any further assumptions. There will, however, be a changed climate in 2050 compared to 2030, and so that change will be reflected in the farm management decisions.

2.4. Adaptation options

Two possible adaption strategies were identified by the case study farmer as the most likely he would use to cope with the impacts of changes in climate and water allocation. The fundamental requirement was to ensure that cotton was kept as part of the cropping mix since there was a high level of expertise invested in both experience and equipment (resulting in high levels of iner-

tia in crop selection decisions) and because of the relative high profitability of cotton.

The two strategies represented different spacing between rows and different irrigation amounts. Strategy 1 allowed the substitution of some of the baseline production system with a system of less intensive cotton planted at 2 m row spacing instead of 1 m, with a maximum of two in-crop irrigations instead of four and, with the same planting rules, except the availability of 2 ML/ha stored water instead of the previous 4 ML/ha (Table 2). Strategy 2 allowed for the production option of dryland cotton planted on a 2 m row spacing. The second strategy implied that as much 2 m row spacing cotton was planted as possible depending on the other cropping rules regardless of the state of the storages. The baseline scenario was the current production system (Tables 2 and 3) and was run with current climate (1960–2010).

3. Results

3.1. Crop yields

The simulations of the grain-cotton enterprise showed that without any adaptation to climate change, such as changes to planting or irrigation strategies, the median cotton yield (t/ha) increased slightly in the 2050 s (Fig. 3). However, the area of cotton that could be planted decreased by 19% in the 2030 s and 35% in the 2050 s (Table 5). If Strategy 1 was pursued (Fig. 4a) (2 m rows and partial irrigation), there was a decrease in yield of 12.1% in 2030 and 4.4% in 2050 compared to the baseline case. Under Strategy 1, the area of cotton planted at 1 m row spacing was reduced in 2030 by 21.2% from 73.0 ha to 57.5 ha, and by 19.2% to 59 ha by 2050. However, the overall area of cotton could be increased by 36% and 38% in 2030 and 2050, respectively, because of the inclusion of irrigated cotton planted at 2 m. With Strategy 2 (Fig. 4b), the area of 1 m planted cotton was reduced by 45% in 2030 and 2050, but the total area of cotton increased by 90% from the baseline in 2030, and 67% in 2050 (Table 5) because of the inclusion of dryland cotton. Furthermore, the proportion of low yields (i.e. <5 bales/ha) increased over the same periods under Strategy 2. If such low yields were to occur

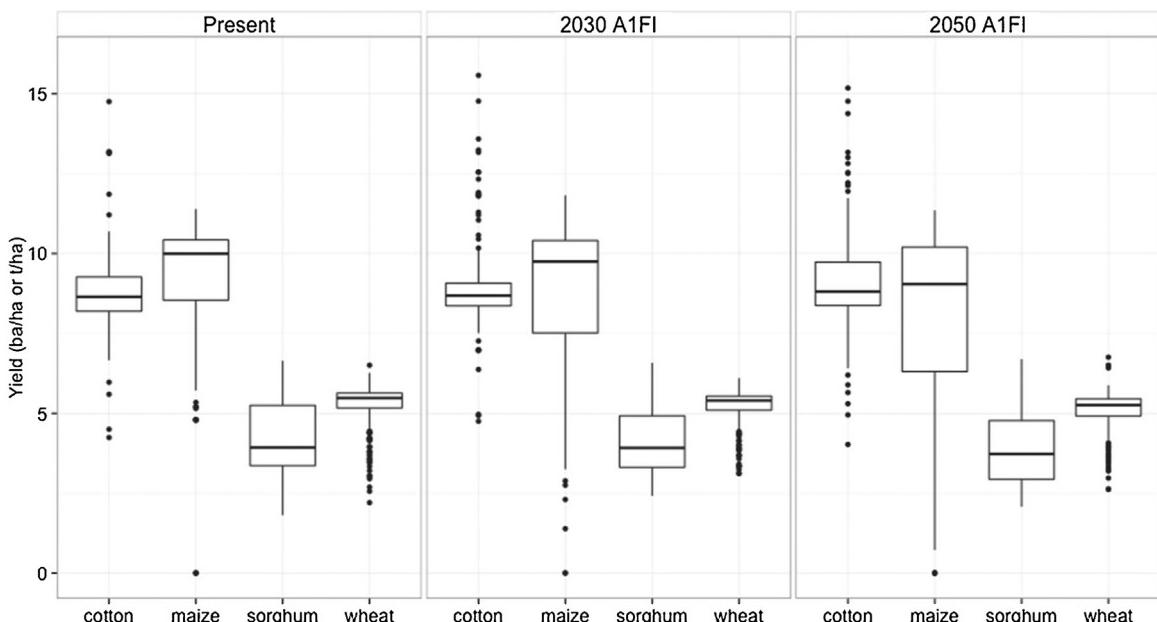


Fig. 3. Yields using no adaptation strategy to future climate change. That is, 1 m planting and full irrigation under both present conditions and future conditions (years 2030 and 2050) with the A1FI scenario and a 14% reduction in water allocation.

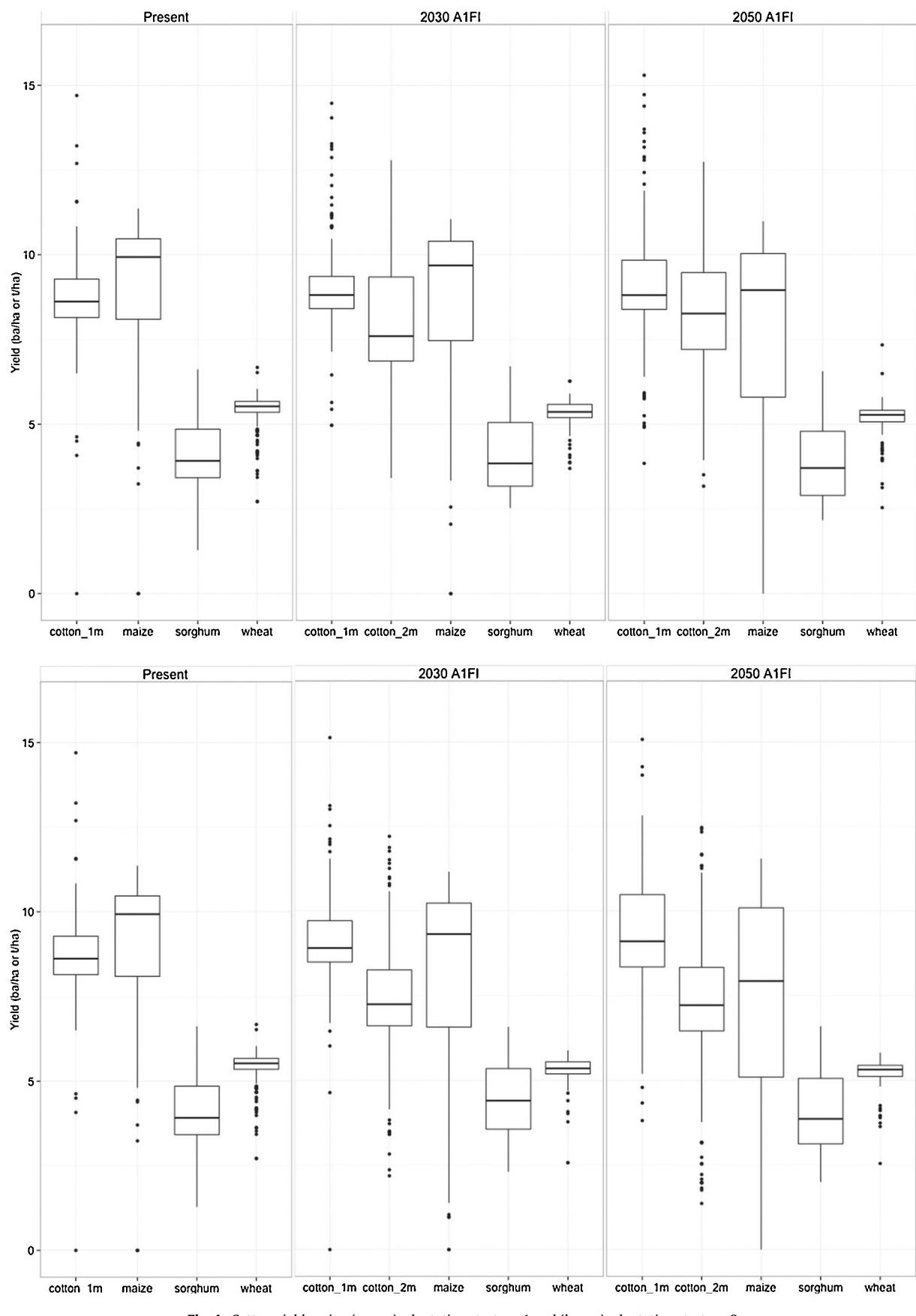
**Fig. 4.** Cotton yields using (upper) adaptation strategy 1 and (lower) adaptation strategy 2.

Table 5

Area planted to cotton with and without adaption.

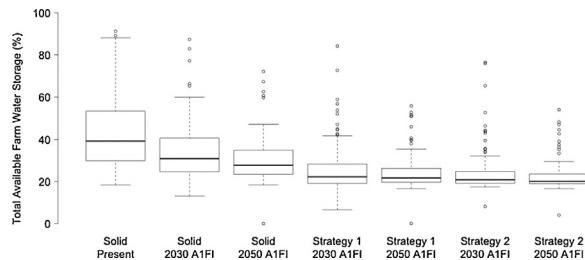
Type of Planting	Area planted (ha)		
	Present	2030	2050
Without Adaptation			
Cotton (1 m)	73.0	58.0	47.0
Strategy 1			
Cotton (1 m)	73.0	57.5	59.0
Cotton (2 m)		42.0	42.0
Total Cotton	73.0	99.5	101.0
Strategy 2			
Cotton (1 m)	73.0	40.0	40.0
Cotton (2 m)		99.5	84.0
Total Cotton	73.0	139.5	124.0

Table 6

Median irrigation applied (ML) to crops with and without an adaptation strategy.

Crop	Without Adaption			Strategy 1		Strategy 2	
	Present	2030	2050	2030	2050	2030	2050
Cotton 1 m	257	210	170	182	181	103	92
Cotton 2 m	—	—	—	73	66	219	197
All Cotton	257	210	170	255	247	322	288
Maize	53	69	57	55	57	52	54
Wheat	143	144	129	105	100	108	71
Total ^a	425	351	335	359	319	364	326
% sourced from bore	47	49	52	48	55	47	53

^a The total is calculated for each growing season for the whole and is not the sum of the crop medians.

**Fig. 5.** Available water storage at start of crop year.

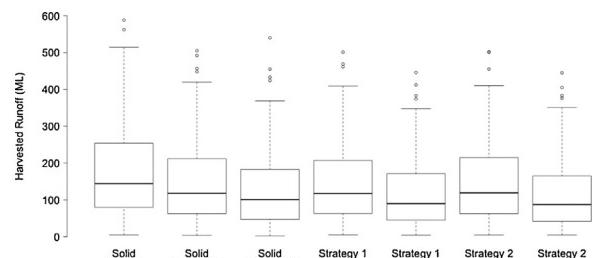
in consecutive years, such as during a prolonged drought, then the losses incurred by the farm might be significant.

Yields from the 2 m row spacing increased by a similar margin to the solid planting (largely due to CO₂ fertilisation; Williams et al., 2015). However, there was an increase in the year-to-year variation in cotton yields compared to continuous solid planting of cotton because of the increased reliance on in-crop rainfall. Median yields were similar between the strategies, but the inter-annual variability of yield increased under Strategy 2 (Figs. 4a and 4b).

3.2. Water use and availability

The total irrigation applied to the simulated cotton crop under the present climate was 257 ML. Under the climate change scenario utilised, the amount of water harvested and water applied was greater for Strategy 2 (Table 6), even though there was less rainfall. This is due to the increase in cropping area creating greater demand for irrigation and, hence, an increase in the capacity to harvest water. The increase in applied irrigation water resulted in reduced production per ML.

There was 14% less water available in 2030 and 2050, which reduced input costs. Although there was a decline in 2030 and 2050 and on one occasion the storage was exhausted, an excess water available without adaption could be observed (Fig. 5). The

**Fig. 6.** Harvested runoff during the crop year.**Table 7**

Median yield and Gross margins for cotton growing using 1 m (solid) row spacing and the two adaptation strategies with cotton grown at 2 m under the A1FI scenario and the CSIRO Mk3.5 model.

	Present	2030	2050
Yield (Bales/ha)			
Cotton 1 m only	8.7	8.8	8.9
Strategy 1		7.6	8.2
Strategy 2		7.2	7.2
Gross Margin (\$/ha)			
Cotton 1 m only	813	828	817
Strategy 1		1145	1094
Strategy 2		1174	1146
Farm Gross Margin (\$)			
Cotton 1 m only	253,701	186,431	144,688
Strategy 1		276,050	232,478
Strategy 2		329,154	273,321

adaptation strategies made greater use of stored water and hence had lower harvest levels, but rarely to less than 20% of capacity. This could well be an effective strategy for producers who are "risk takers".

The reduction in rainfall did not have a simple linear relationship with the amount of runoff harvested into water storages. When storages were run down, there was a greater capacity to harvest run-off, and conversely a reduction in harvested runoff without adaptation although this outcome did not change significantly for the two adaptation strategies (Fig. 6). This suggests that the model used to capture runoff was quite conservative.

3.3. Gross margins

Farm financial variables were calculated as total gross margin (farm level), crop gross margin and crop gross margin per ha. Without adaption, the total gross margin was reduced by 27% (from \$253,701 to \$186,431) in 2030 and 43% (from \$253,701 to \$144,688) by 2050 (Table 7). The losses were largely due to the reduction in irrigated crops even though sorghum showed a 22–23% increase in crop gross margin.

Adaptation Strategy 1 resulted in an 8.8% increase in the total gross margin by 2030, but a 15.8% decrease by 2050 (i.e. a 7.8% decrease compared to the present). However, with dryland cotton in the rotation (adaptation Strategy 2) there was an increased farm gross margin of 49% by 2030 and 12% by 2050 (Table 7). Gross margins for cotton grown on 2 m rows were greater than when grown with 1 m rows because the latter has a greater irrigation requirement and higher costs in terms of establishment. However, if cotton on 2 m rows was grown to the exclusion of cotton grown on 1 m rows then overall production was reduced. Farm level gross margins increased in 2030 and 2050 because the area of cotton planted increased under both adaptation strategies (Table 5).

4. Discussion

This study took farm level crop modelling a step further by integrating the production of cotton with decisions that have to be made about the allocation of limited resources. The main limitation considered in this study was the use of water given likely future access and volume restrictions due to climate change and national government water policies. Water security is essential for cotton producers to be able to plan, invest in, and irrigate or water stock (Mushtaq, 2016). Many farmers, especially cotton producers, have invested considerable sums of money in new irrigation systems and on-farm technologies to cope with changes to the water availability and to enhance water use efficiencies. Yet they are struggling to cope with the uncertainties surrounding water policies that can influence future water allocations and water supplies (Kiem, 2013; Wei et al., 2011).

Understanding crop level responses using APSIM at the paddock level can provide a great deal of information about the likely response in terms of yield. However, farms tend to be more complex with a range of crops, markets and resource limitations to consider. The modular nature of a farm-level APSIM provides a way to consider other planting strategies and crops. It also helps as a set of rules can be developed to simulate the decisions made at the farm scale. This can be set against historical or future climates and can be used to consider the implications of government water policies developed at a higher level. In addition to considering the changes in rainfall that are likely to occur in 2030 and 2050, we also considered in our study the policy implications of the Murray Darling Basin Plan (MDBA, 2012). This is an evolving suite of policy and legislation and specific decisions of the future can be easily included in the framework at some point in the future.

In general, the study region is projected to receive less rainfall and consequently reduced inflow to the rivers and on-farm storages. Therefore, the amount of irrigation water available would reduce and restrict the area of land that can be irrigated. Specifically, we used a modest 14% reduction in bore allocation, coupled with reduced overland flow due to decreased rainfall. Adaptation to climate change and reduced water allocation was introduced into the simulation by considering opportunities for partial irrigation and dryland planting of cotton at wider row spacing. A mechanism was included by which cotton was preferentially retained in the mix of crops because an enterprise that is built around cotton is likely to remain so unless very strong forces act upon it. The other crops (wheat, maize and sorghum) retained with the present agro-economic conditions and water requirements. Williams et al. (2015) showed that initially cotton responds favourably to changes in climate variables and CO₂ fertilisation with an increase in yield of 5.9% by 2030. However, the cotton yield decreased by 3.6% by 2050 when the climate became unfavourable for crop growth and it was no longer offset by CO₂ fertilisation. Regardless of the uncertainty in rainfall projections, it is likely that water stress will increase due to the rising temperatures and decrease in water balance. This will lead to an increasing focus on water use efficiency, water access and soil water management.

This study demonstrated that without adaptation, overall farm gross margins would decrease due to the combination of climate change and government policies reducing irrigation water availability. The two adaptation scenarios explored here demonstrated that it is possible to have a productive farm enterprise in the future in the Darling Downs and that current cropping regimes could be adjusted. The long-term gross margin is indicative of the capacity of the system to cope with change. Individual farm level studies would need to be done on a case-by-case basis to investigate the profitability of specific farms.

One of the benefits of farming in a region historically prone to significant annual and seasonal climate variability is that producers

have relatively high levels of diversification. This may well enable them to consider adaptation options with greater ease compared with farmers who have not had to incorporate strategies to overcome climate variability. If suitable adaptation techniques can be utilised then the impact of the loss of water through both climate change and water policy can be reduced. Cotton appears to be relatively adaptable to drought because its production is relatively flexible (Loch et al., 2013; Prosser, 2011). However, the industry already practices a high degree of water efficiency and therefore the best adaptation strategy may be through planting strategies such as 2 m cotton with partial irrigation, rather than substantially changing the way the crop is irrigated.

The adverse impacts of climate change and reduced water allocation can be partially offset with appropriate adaptation applied to cotton production. A more complete investigation could be undertaken whereby the whole farm enterprise is optimised. However, this was outside the scope of this study since we were primarily interested in demonstrating the utility of the approach when considering possible adaptation strategies. There are benefits to utilising both biophysical models and expert knowledge to enhance our understanding of the impacts of climate change and government policies on crop production and the most effective ways to adapt.

There are many studies that link climate with cotton and agricultural outcomes such as yields and farm profits. This study has used a theoretical model incorporating plant-growth theory in a simulation model to estimate links between climate, water availability and cotton yields. This complex and dynamic approach addresses physiological processes that are not easily estimated in regression frameworks. However, there are caveats that need to be acknowledged including model complexity, uncertainty about some of the processes, and the large number of parameters. In addition, the model sensitivity will vary depending on the specific future climate scenario selected (different General Circulation Models produce different future climate scenarios), although the pattern of change from 2030 to 2050 is likely to be constant.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.agwat.2017.10.026>.

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